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TITLE

Electrooculography: Connecting mind, brain, and behavior in mathematics education research

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ABSTRACT

This paper reports on the potential roles and importance of electrooculography (EOG) for mathematics educational neuroscience research. EOG enables accurate measurements of eye-related behavior (i.e., blinks & movements) by recording changes in voltage potentials generated by eye-related behavior. We identify and discuss three main uses of EOG. First, EOG provides insights into cognitive function. Secondly, it is used to attenuate eye-related artifacts in electroencephalography (EEG). Thirdly, EOG serves as a helpful means for calibrating covert brain activity with overt behavior. We provide an overview of the first two application areas, and we illustrate the third application using an example data set capturing an "aha moment" in our research in the area of mathematical problem solving.

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ABSTRACT (117 WORDS); PAPER (2879WORDS); REFERENCES (439 WORDS).

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Introduction

Many educational researchers are concerned with understanding how teachers and learners are thinking. That is to say, many educational researchers are concerned with understanding what is going on in the minds of teachers and students to better assess what they know, how they know it, and thereby to help design pedagogies that can lead to improvements in helping these populations to be educated more effectively. Traditionally, educational researchers engaged in the empirical study of cognition and learning have relied upon overt behavioral data gathered from interviews, field notes, self-reports, and audiovisual recordings. In focusing on overt behavior, educational researchers have typically not been privy to what is happening covertly, with regard to the physiology of these populations. To the extent that cognition and learning are embodied behaviors, it would be helpful to augment these traditional data sets with physiological data sets whenever possible and to the extent that it is practical to acquire them. We know from cognitive neuroscience and psychophysiology, that there is much to be gained from informing educational research with results from these well-established fields. Educational neuroscience is attempting to accomplish just that. As educational neuroscientists, one challenge we have encountered in so doing concerns how best to connect our traditional overt data sets with the covert behavioral data sets, specifically, in our case, electroencephalography (EEG), to obtain deeper educational insights into cognition and learning.

One way of investigating connections between these overt *audiovisual* (AV) data sets with covert physiological recordings is through *eye-related behavior* (ERB), which can be observed using *electrooculography* (EOG) and *eye-tracking* (ET) technology. In this paper, we focus on the potential roles and importance of EOG for mathematics educational neuroscience research. Electrooculography enables accurate measurements of ERB (i.e., blinks & movements) by recording changes in voltage potentials generated as a consequence of ERB. We identify and discuss three main uses of EOG. First, EOG provides insights into cognitive function. Secondly, it is used to attenuate eye-related artifacts in EEG. Thirdly, EOG serves as a helpful means for calibrating covert brain activity with overt behavior. In this paper, we present some background regarding educational studies concerning ERB using ET and describe EOG. We then provide an overview of the first two of the three aforementioned application areas for EOG. We illustrate the third application area using an example data set capturing an "aha moment" obtained in the course of our research in the area of mathematical problem solving.

Background

A major reason for growing interest in educational neuroscience in mathematics education research, aside from the now widespread recognition that cognitive constructs are embodied, is a need for better empirical grounds for developing theories of mental functions and processes (Campbell, 2006 a, b). This, in turn, can reconstitute the conceptual basis for more effective forms of mathematical learning and instruction. According to Byrnes (2001), brain research is relevant to the field of psychology and education to the extent that it fosters better understandings of mind, development and learning. The validity, reliability, and relevance of psychological theories of teaching and learning developed from traditional psychological experiments may variously be corroborated, refined, or refuted through neuroscientific studies or the use of neuroscientific tools and methods to test hypothesizes of any particular theoretical account (cf. Byrnes, 2001; Kosslyn & Koening, 1992).

Conversely, research in the neurosciences can also benefit from the more situated and ecologically grounded insights into cognition and learning that typifies the concerns and aims of educational research. Accordingly, educational research that informs and is informed by neuroscientific research, while incorporating methods of cognitive neuroscience with the further aim toward corroborating, refining, or refuting certain models of cognition and learning — that is to say, educational neuroscience — should become of abiding interest and concern to educators and educational researchers alike. This interest includes, beyond standard methods of data collection in educational research, analyses of EEG data sets measuring bioelectrical signals generated from brain activities engaging cognitive processes, such as those involved in mathematical thinking.

Theoretical considerations concerning brain dynamics and embodied cognition aside, there are also methodological challenges in isolating brain activity with EEG and in calibrating EEG with other eye-related behavioral data sets, such as EOG and ET, along with traditional behavioral data sets, such as AV recordings. As our main objective here is methodological, we turn now to ways in which EOG can help address these matters.

Electrooculography

In the middle of nineteenth century Emil du Bois-Reymond observed that the cornea of the eye is electrically positive relative to the back of the eye, forming a so-called corneoretinal potential in the range of 0.4 - 1.0 mV (Malmivuo & Plonsey, 1995). Since this potential was not affected sufficiently by light or any other environmental conditions, it was considered as a resting potential. As the eyes move, each of them behave like single dipoles oriented from the retina to the cornea. Eye movements produced these moving (rotating) dipole sources and signals from these sources are measured by EOG in the range of 5-20µV/° (see Figure 1, below). Data are acquired by electrodes placed around the eyes; these electrodes detect the rotations of the electrostatic dipoles. Figure 1 illustrates the kinds of signals generated from horizontal eye movements, as recorded by a bipolar pair of electrodes attached to the sides of the left and right eyes, lateral to the external canthi (just laterally and external to the left and right of each eye).

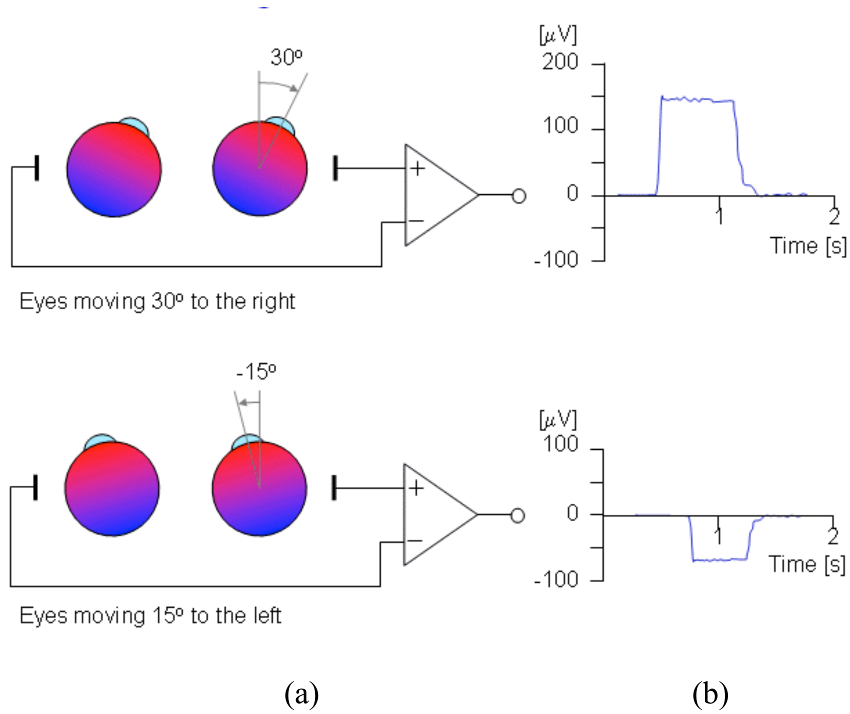


Figure 1: An illustration of the electro-oculogram (EOG) signal generated by horizontal movement of the eyes. The polarity of the signal is positive at the electrode to which the eye is moving (from Malmivuo & Plonsey, 1995).

When the eyes are at rest, the electrodes detect resting potential, so no voltage is recorded. As illustrated in Figure 1, a rotation of the eyes to the right result in a difference of potential, with the electrode in the direction of the movement becoming positive relative to the second electrode. A rotation of the eyes to the left results in the opposite effect. As with most techniques, EOG has both advantages and disadvantages. The main limitation of the method is the difficulties owing to artifacts arising from extraocular muscle activity (see below). The advantages of this technique include minimal interference with eye movements.

Electrooculography as a Cognitive Indicator

It has long been said that the eyes are the windows of the soul. Poetics aside, insofar as the soul is an antiquated term for the mind, it seems reasonable to consider that ERB could provide some indication of various cognitive states, functions, and behavior as well. For instance, ERB, particularly eye-movements, have been studied using ET as an indicator of attention and memory (Kramer & McCarley, 2003), and pupillary response has been studied as an indication of cognitive load (Just, Carpenter, & Miyake, 2003).

Many kinds of mathematical activity are connected with ERB, which can variously be voluntary or involuntary. Reading (including reading mathematical texts) serves as an example of voluntary eye movements and eye movements can be predictable to some extent. Less deliberate to involuntary eye-related behavior are eye-blinking and saccades (rapid macro and micro eye-movements). Behaviorally, the specific character of eye movement during reading is summarized in Duchowski (2002). His study is based on ET research and its application. Duchowski hypothesizes and cites evidence that as the text becomes conceptually more difficult, fixation durations increase and saccade lengths decrease. Eye movement and eye fixation analyses have also been used as a method of research into strategies of successful and unsuccessful arithmetic word problem solvers (Hegarty, Mayer, and Monk, 1995). According to Hegarty, et al's study, less successful problem solvers fixate their eyes on numbers and relational terms when they re-read parts of arithmetic word problem, whereas more successful problem solvers fixate eyes on variable names. They propose that successful problem solvers construct problem models and concentrate their attention on appropriate variable names, whereas unsuccessful problem solvers attempt to directly translate key propositions of these problems into a computational procedure, and thereby remain predominantly focused on numbers.

More generally, studies using EOG provide evidence that blinks and saccades are indicators of cognitive function. For instance, it has long been known that blink rates decrease significantly during visually demanding tasks (e.g., Fogarty & Stern, 1988). Moreover, blinks and saccades evidently serve to punctuate shifting foci of attention, be they exogenous shifts in attention from one object to another, or endogenous shifts in reflection from one line of thought to another (Bonfiglio, Sello, Andre, Carboncini, Arrighi, & Rossi, 2009).

Electrooculography for Artifact Correction

All eye-related behavior (viz., ERB), i.e., eye-movements, eye-blinks, saccades, dilations, and focusing, voluntary or not, are based on extraocular muscles encasing the eyes (see Figure 2), though we should note that other muscles associated with the neck, scalp and face are also implicated with ERB, when, for instance, one is moving one's head and/or wincing.

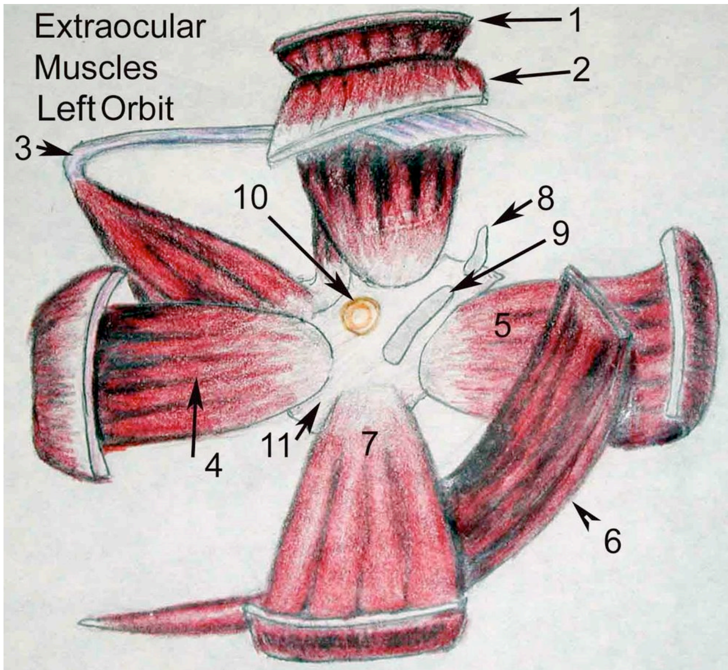


Figure 2: Extraocular muscles: 1) the *Levator Palpebrae Superioris* muscle elevates the eyelid; 2) the *Superior Rectus* muscle makes the eye look upwards or medially or wheel-rotates it medially (intorts); 3) the *Superior Oblique* moves the eye downwards or laterally or wheel-rotates it inwards (i.e. makes twelve o'clock on the cornea move towards the nose); 4) the *Medial Rectus* is the largest of the ocular muscles and stronger than the lateral and is a pure adductor; 5) the *Lateral Rectus* makes the eye look directly laterally in the horizontal plane; 6) the *Inferior Oblique* makes the eye look upwards or laterally or wheel-rotates it; 7) finally, the *Inferior Rectus* makes the eye look downwards or medially or wheel-rotates it laterally. This muscle also serves to depress the lower lid. Other ocular muscles (not shown here) actually enclose the eye.

Voltage potentials from motor neurons of extraocular muscles causing muscle contractions interfere with both EOG and EEG, the latter of which monitors brain activity. We shall see that EOG enables improved correction of these interfering potentials in EEG data, thereby improving the quality of EEG data and subsequent EEG analysis and interpretation.

EOG data also enable time synchronization and integration of EEG with ET and AV data sets by calibrating EOG data with these data sets.

According to Kierkels, Boxtel, and Vogten (2006), before brain activity measured by EEG through scalp voltage potentials is analysed — especially, we would add, in single trial (non-replicable) conditions — ERB artifacts should be identified and attenuated using signal processing techniques. Figure 3 illustrates ERB artifacts in EEG data.

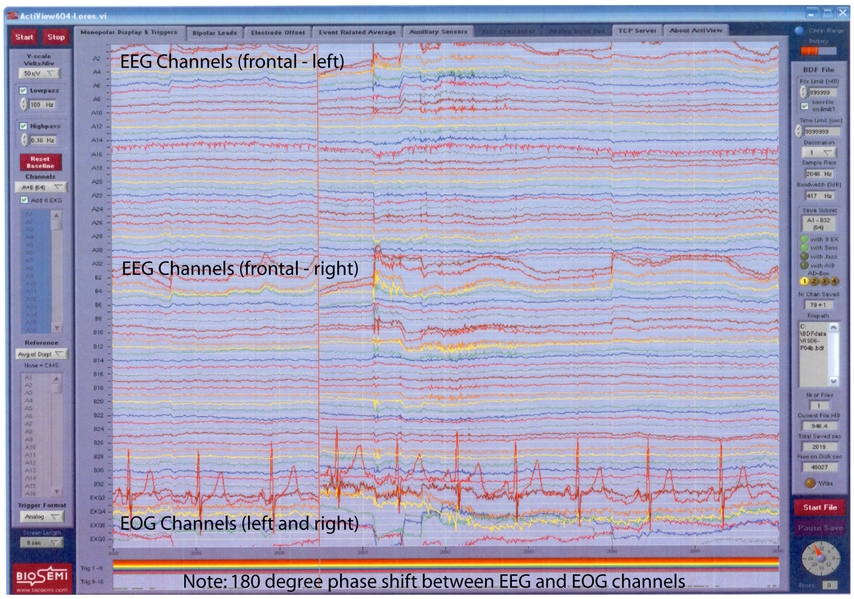


Figure 3**:** This raw data set illustrates strong eye-related artifacts, evident in the EOG channels in the bottom of the figure, in the rightmost two thirds of the figure in the frontal EEG channels, which are closer to the eyes (in this case, the upper and middle channels).

It is helpful to mention here that when analyzing EEG data, the signals generated by ERB, as well as any other voltage potential signals of non-cerebral origin, should be treated as artifacts (i.e., undesired signals). Puthusserypady (2005) notes that ERB signals are typically the most significant and common artifacts in EEG, and that removal of ERB signals from EEG data forms an important part of preprocessing of EEG data prior to EEG analysis. Eye blink signals are of high amplitude. Indeed, they can be as much as ten times the amplitude of signals due to brain activity recorded from the frontal EEG channels, and they are low frequency in nature and affect the low frequency range of EEG signals. Kierkels et al (2006) point out that ERB signals have large disturbing effects on EEG recordings because the eyes are located so close to the brain.

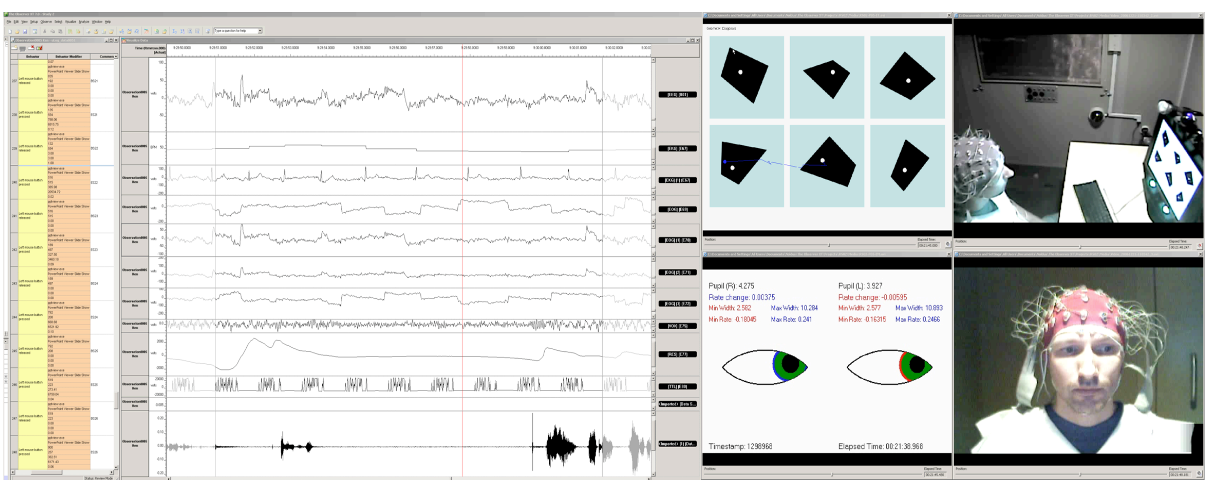
There are many methods for eye movement correction in EEG recordings reported in literature, with varying degrees of success (Kierkels, et al, 2006; Croft, Chandler, Barry, Cooper, & Clark, 2005). Ille, Berg, and Scherg (2002), for instance, distinguish between methods that remove ERB signals from EEG data without considering brain activity and those that do attempt to separate artifacts and brain activity. In the former case, in multi-trial studies, signals that exceed a threshold criteria, such as maximum amplitude, beyond which are typical of eye-blinks, are rejected whole scale, together with the EEG data. In the latter case, these authors also consider signal processing methods, such as Principle Component Analysis (PCA), Independent Component Analysis (ICA), Multiple Source Eye Correction (MSEC), that are designed to separate ERB artifacts and EEG brain activity, as promising methods for future development. In our presentation (see Appendix I), we demonstrate the ICA method for separation ERB signals from brain activity signals by subtracting components related to ERB from EEG data.

Electrooculography for Calibrating Data Sets

We use EOG recordings in tandem with ET and AV data sets to synchronize with EEG data sets, which are indirect recordings of the electrical component of the biopotential field recorded on the scalp being generated from brain activity. We illustrate our approach with a data set capturing an “aha moment” during a mathematical problem solving task. It should be mentioned here that the mathematical problem solving experiments are principally of so-called ‘single trial’ type as they cannot be fully replicated or repeated, either with regard to stimuli or thought processes. Every such experiment is a unique combination of cognitive process that requires observations of high signal fidelity and integrity for analysis. In integrating overt and covert behaviors associated with problem solving events, we aim to explore the extent to which valid and reliable information can be obtained from single trial studies in mathematical problem solving.

In the single trial data set we present, the mathematical problem task was based on the paradigm of Dehaene, Izard, Pica, & Spelke (2006). These data involve a slide comprised of six diagrams of different kinds of quadrangles: Five of the six diagrams were connected by a common mathematical concept of 'diagonals of the quadrangles'. Note that the dots inside of five of the six diagrams were located exactly at the intersection the diagonals; the task was to identify the diagram that did not conform, that is, the diagram where the dot inside the quadrangle is not located at that intersection. This paradigm was presented on the screen of a computer to one male participant, aged 38 years and 3 months.

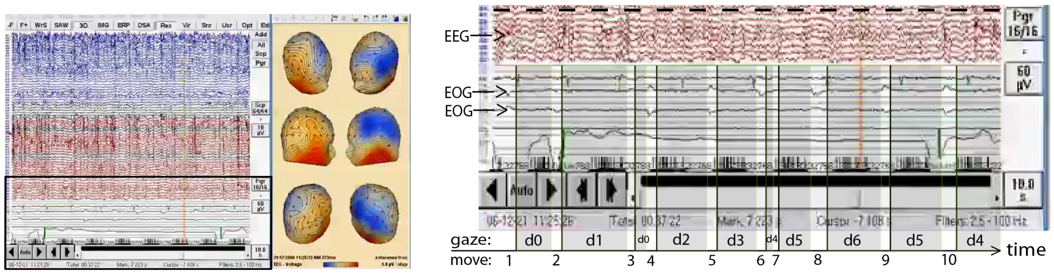
Although we are certainly interested in removing ERB signals from EEG data (again, see Appendix I), we are also interested in using EOG data to synchronize brain activities manifest in EEG with our eye tracking data and with our audiovisual behavioral data (see Figure 4).



(a) (b)

Figure 4**:** An integrated time-synchronized data set. Notice that EOG channels 4 and 7 (from the top in figure 4a) express the dipole characteristics schematized in Figure 1b.

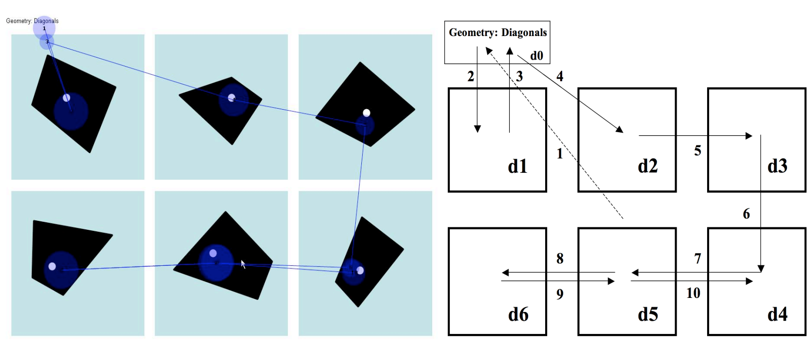
Figure 5 is a frame from a movie file demonstrating the process of thinking on this problem in terms of EEG and EOG signals. We demonstrate the utility of EOG data to help accurately calibrate, i.e., time-synchronize these brain data with the behavioral data.



(a)	(b)

Figure 5**:** Fragment of movie demonstrating the process of mathematical thinking (and "aha moment") in terms of EEG, EOG and respiration signals (a); detailed segmentation of EEG data on the basis of EOG waveform analysis (b).

Figure 6 provides a detailed breakdown of 10 saccades, beginning with the initial eye movement "1" terminating at "d0", which is the text region in the upper right corner of the slide, followed by eye movement "2" down to diagram "d1" and so on. The expansion of the ancillary channels in Figure 5b shows data obtained from the EOG electrodes, attached just off the corners of the participant's left and right eyes, highlighting "gaze" regions (d0, d1, ..., d6), and eye "move(ment)" events (1, 2, 3, ..., 10). The annotations in Figure 5b correspond to the annotations indicated in Figure 6b. The shaded areas in Figure 5b denoted by the gaze regions indicate when the participant was attending to the six diagrams in the slide in Figure 6a, with "d0" indicating the text region to the upper left. These annotations are most clearly indicated in Figure 6b.



(a)	**(b)**

Figure 6: Actual eye-movements on the screen stimulus, following Dehaene, Izard, Pica, & Spelke (2006) (a), and a schematization of those movements (b).

Getting accurate calibrations are crucial to properly associating covert brain activities with overt problem solving tasks. Once these data sets are synchronized, a more integrated approach can be taken in connecting brain and behavior. Such integrated approach serves as method for validation and reliability of mathematical problem solving data interpretation. Our interpretation of these data is an entire topic of its own, and as such, is left for another time.

Conclusion

Eye-related behavior can be used to infer cognitive function and to operationalize human performance. From a cognitive perspective, it can be variously considered as sensory-driven, emotionally-responsive, or goal-directed. In terms of performance, eye-related behavioral indexes, like fixation patterns and gaze durations, can operationalize efficiency and workload. Hence there are implications for both studies in cognition and learning, and instructional design and usability of educational software. Eye related behavior manifest in EOG signals thereby serve as indicators of various aspects of cognition and performance, including aspects of attention and memory evident in mathematical problem solving. Eye-related behavior evident in EOG can be both a blessing and a curse, however, insofar as ERB activity interferes with EEG recordings that may provide further insights and indicators in this regard. Fortunately, EOG signals can be used with signal processing methods such as ICA to help attenuate those artifacts from EEG data. Finally, it is evident that EOG data can serve as a bridge in connecting EEG and other physiological data sets with more overt behavioral data sets such as eye-tracking and audiovisual data sets. Indeed, EOG serves well in a variety of ways in connecting brain and behavior, thereby increasing the validity and reliability of single trail studies. We hope to have demonstrated that EOG has important methodological roles to play in helping to establish educational neuroscience as an important and viable new area of educational research.

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Appendix I

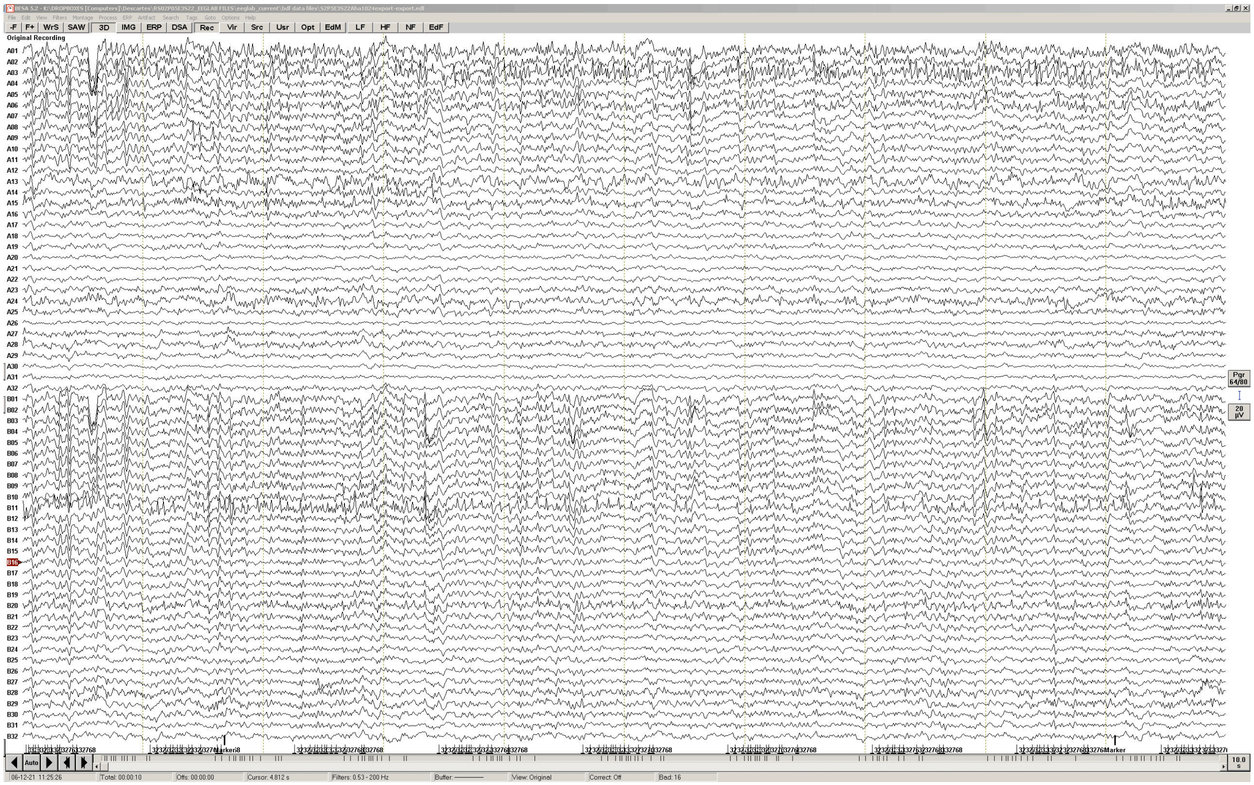

Figure A1: Raw EEG data.

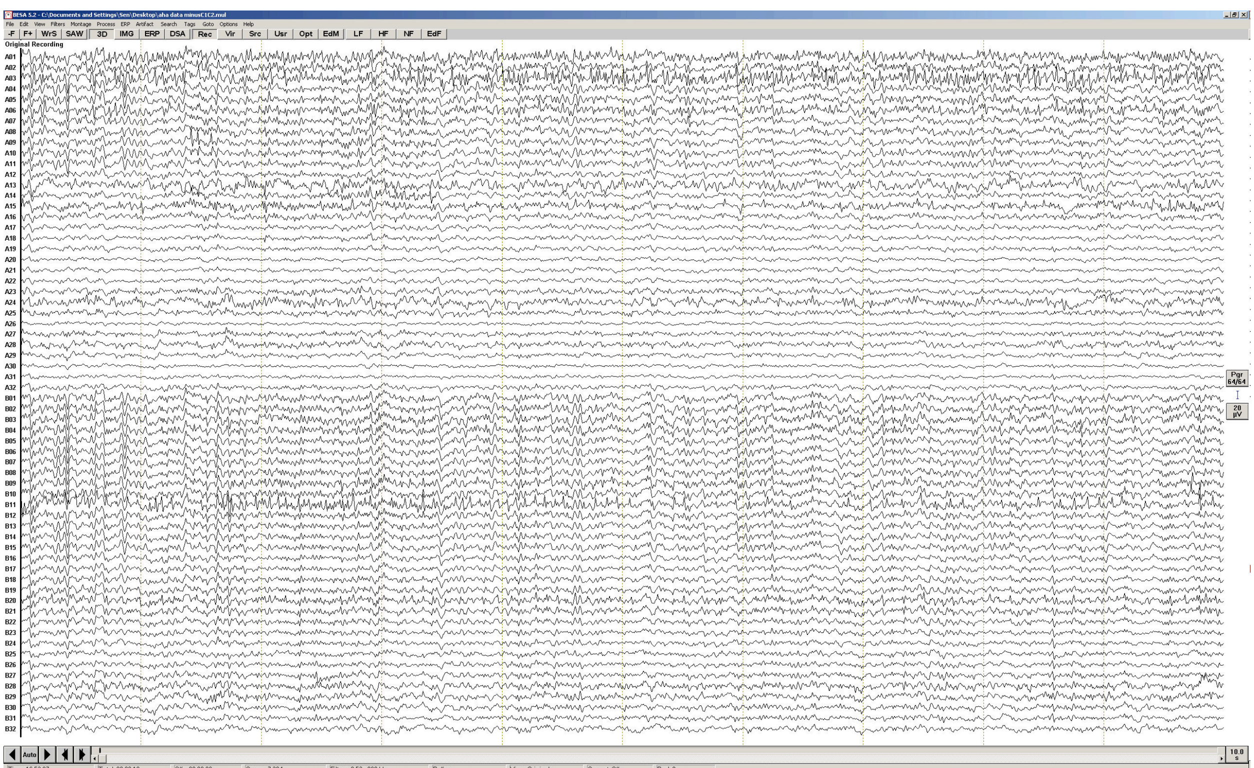

Figure A2: Raw EEG data with vertical (A3) and horizontal (A4) eye movements removed.

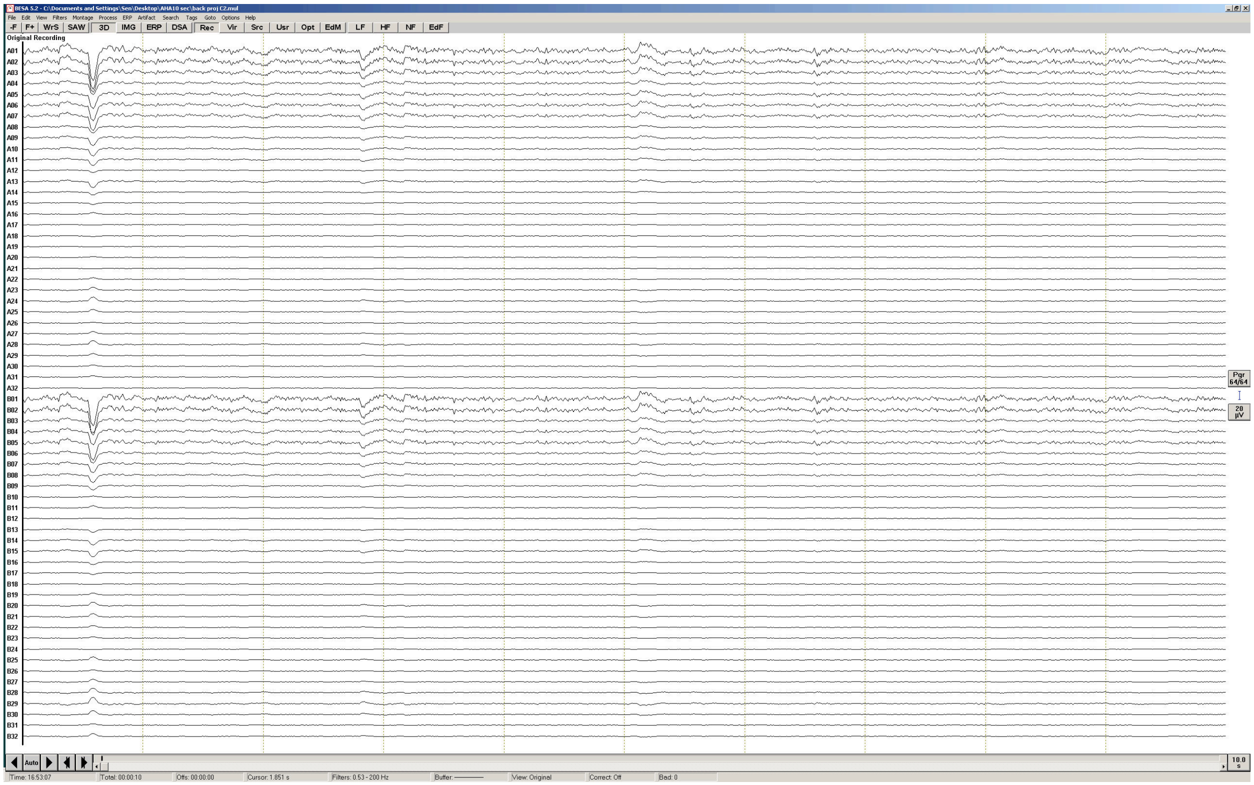

Figure A3: Vertical eye movement component extracted using ICA.

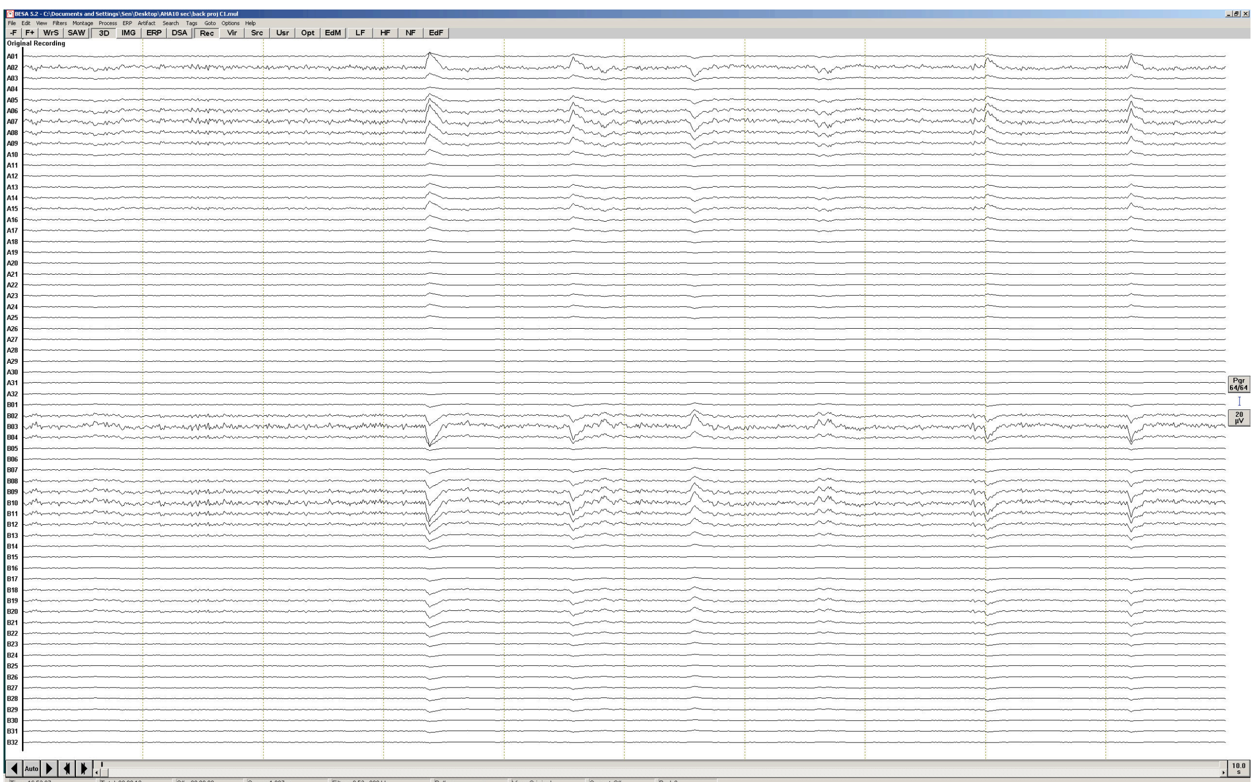

Figure A4: Horizontal eye movement component extracted using ICA.